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Solar-assisted multi-stage vacuum membrane distillation system with heat recovery unit

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HIGHLIGHTS

- Design and performance evaluation of a SMVMD system with HRU and TM scheme
- Development and validation of an integrated theoretical SMVMD model
- Performance evaluation of a multi-stage VMD system for the different numbers of HRUs
- Annual performance evaluation of a SMVMD desalination system

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ABSTRACT

This paper describes the development of a solar-assisted multi-stage vacuum membrane distillation (SMVMD) system. The proposed system employs heat recovery unit (HRU) for the energy recovery from the permeate vapor to the feed seawater. Temperature modulating (TM) scheme is also implemented for the attenuation of temperature fluctuations of the feed seawater. A commercial shell-and-tube capillary membrane module consisting of an array of polypropylene hydrophobic fibers has been adopted for the system design and mathematical model development. The SMVMD system is studied for the different numbers of HRUs using a mathematical model. For a solar-assisted VMD system with 24-stage, the total water production of SMVMD system with 10 HRUs is found to be 3.37 m^3/day, which is about 34% higher as compared to the system with a single HRU. For a VMD system without solar-thermal unit, the overall specific thermal energy consumption (*OSTEC*) decreases by 20% with an increase in the number of HRUs from 1 to 10. For the different numbers of HRUs in the range of 1–10, the system *OSTECs* with solar-thermal system having 150 m^2 of evacuated-tube collectors and 16 m^3 seawater storage tanks are 28%–36% lower compared to those without the solar thermal system.

1. Introduction

According to the World Health Organization (WHO), the benchmark level of renewable fresh water for a person in a year is 1000 m^3 and any amount below this benchmark is considered to be chronic water scarcity and it would impede human development and harm human health. Water supply in many areas of the world is less than this benchmark and if appropriate steps are not taken to develop sustainable water resources an acute water stress is bound to become more widespread. Furthermore, over 97.5% of the total global stock of water is saline which constitutes a principal source of drinking water on our planet [1]. Therefore, desalination has been the principal short- and long-term strategic option for main potable water resource in many countries around the world. The cost associated with conventional desalination technologies such as multi-stage flash or reverse osmosis, however, imposes as a main barrier for third world countries to adopt desalination as the primary resource of drinking water. Additionally, the dependence of conventional desalination on terrestrial fuel poses a major environmental concern. Desalination plants consume a huge amount of energy for converting seawater to potable water, technically expressed in terms of electrical equivalent in kWh/m^3, from a supportive dedicated power plant. The energy input to the desalination process is directly proportional to carbon dioxide emission via the burning of the fossil fuel. As environmental and energy issues have been greatly intensified, therefore, development of alternative energy-efficient, environmentally-friendly and yet cost-effective desalination processes has become a necessity.

In recent years, alternative desalination technologies, such as membrane distillation (MD) and forward osmosis (FO), have been extensively

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studied. Among these seawater desalination and purification technologies, MD process possesses many attractive features compared to other technologies, especially when coupled with low-grade waste heat or solar energy. Some salient features of MD are; (i) theoretically 100% salt rejection, (ii) low operating temperature and pressure, (iii) low energy consumption when waste heat is available, (iv) low sensitivity to salt concentration, (v) high potential for the utilization of a low grade heat (i.e., solar energy or waste heat), (vi) no extensive pretreatment and (vii) simple membrane construction [2–6]. MD process has been applied for desalination [7–10], waste water treatment [11] and even radioactive waste treatment [12,13]. The performance evaluations of MD desalination systems utilizing solar energy have been also conducted experimentally or theoretically with commercial and laboratory-made membranes [9,14–23].

Likewise, MD process has been proved to be a promising solution for seawater desalination at bench-scale [24]. Furthermore, the Memstill® process has recently been tested for several thousands of hours in bench scale tests and three pilot plants on both artificial and real seawaters. Experimental results showed the potential of membrane distillation for seawater desalination without any scaling or biofouling problems during the tests [25]. One major drawback of MD process, however, is the high energy consumption. For instance, the energy requirements in the vacuum membrane distillation (VMD) are of three types: (i) heat energy for heating the seawater on the feed side, (ii) pumping energy for circulating the seawater on the feed side and (iii) vacuum energy for applying the low pressure on the permeate side [18]. Here some of its thermal energy consumed can be salvaged by recovering the latent heat of condensation of the permeate vapor and the sensible heat from brine stream. It is noted that the thermal energy consumption takes up more than 98% of the total energy consumptions and increases drastically with rise in feed temperature [18]. MD desalination process, thus, will be economically competitive in situations where low-grade waste heat or renewable energy such as solar and geothermal energy is available.

Here, the primary objectives are (i) to design a solar-assisted multi-stage VMD (SMVMD) system with the heat recovery unit (HRU) and temperature modulating (TM) scheme for seawater desalination, (ii) to develop a detailed mathematical model for the system performance evaluation in terms of distillate production and specific energy consumption, (iii) to examine the effect of HRU configuration and solar-thermal system on the process performance and (iv) to evaluate the annual performances of SMVMD desalination system with respect to evacuated-tube solar collector area and seawater storage tank volume. The performance evaluation will be based on the simulations with the meteorological data (i.e., solar radiation and ambient temperature), evacuated-tube collector, seawater storage tank and plate heat exchanger models, which were developed in our previous works [21,26]. Numerical models for the VMD and heat recovery unit are developed in this study and validated with experimental data [27].

2. System description

A schematic of the proposed SMVMD desalination system is illustrated in Fig. 1. The system consists of the solar-thermal system (STS) with temperature modulating (TM) scheme and the multi-stage VMD modules with shell-and-tube heat recovery unit (HRU).

As shown in Fig. 1, the STS has two main circuits: the primary solar hot water circuit that collects the solar energy via a evacuated-tube collector (ETC) array and the secondary circuit which stores the solar heat via a plate heat exchanger (PHE) and supplies the hot feed seawater to the VMD modules through the four seawater storage tanks and TM unit. The four storage tanks in secondary circuit are assembled in a

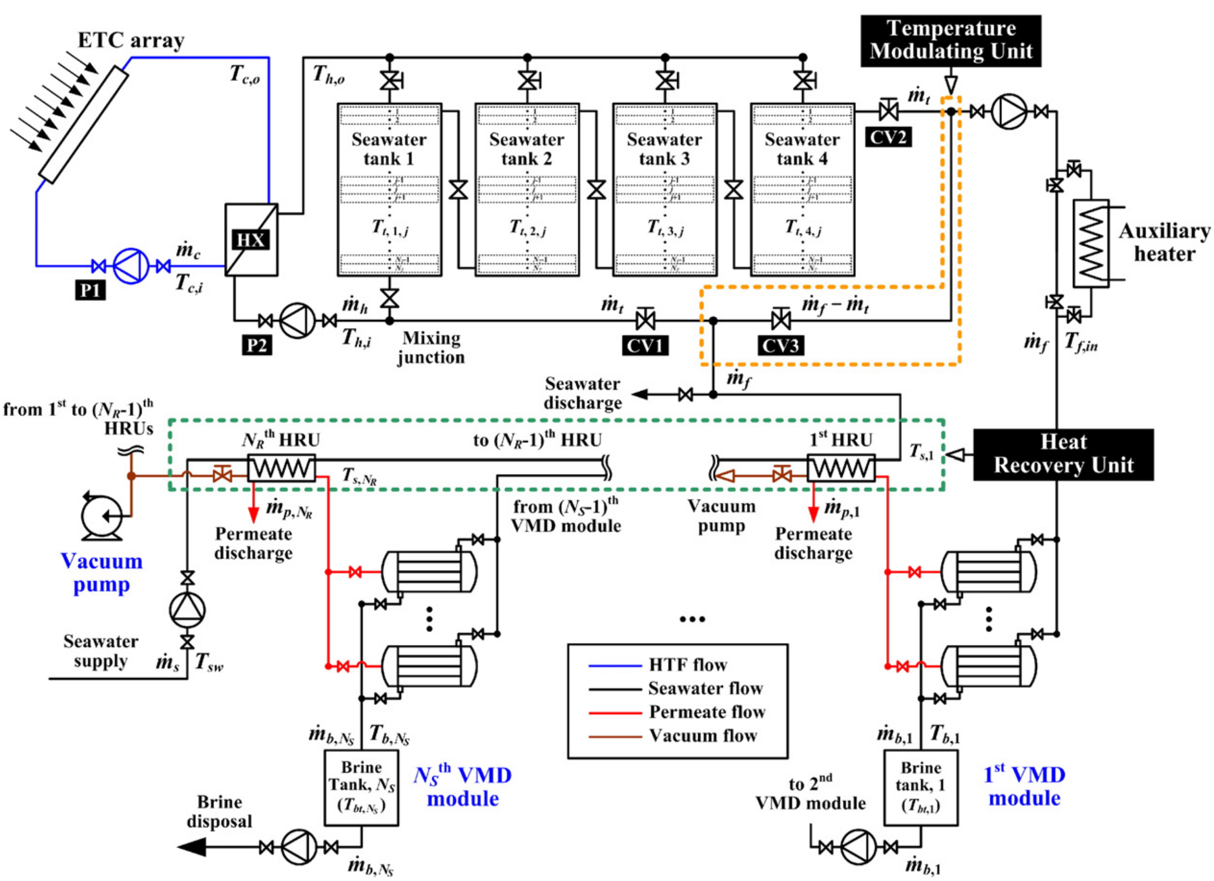

Fig. 1. Schematic diagram of solar-assisted multi-stage VMD desalination system with the HRUs and TM scheme.